national accelerator laboratory

EXP-27
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ACCELERATOR EXPERIMENT--Decoupling of Radial and Vertical Betatron Oscillations at High Energy in the Main Ring

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1. Introduction

Though we have had evidence of various sorts since last December of a rather strong coupling between radial and vertical betatron oscillations in the main ring, the present experiment represents the first quantitative examination of the phenomena. For a number of reasons, the experiment was carried out at high energy. Near injection energy, betatron oscillation studies in the main ring have always defied detailed interpretation; indeed, early in this work an attempt to obtain understandable results at injection was unsuccessful. At high energy, one may hope that linear coupling effects can be isolated, which, when removed, may facilitate analysis of the low-energy region, as well as reduce the vertical emittance of the slow extracted beam.

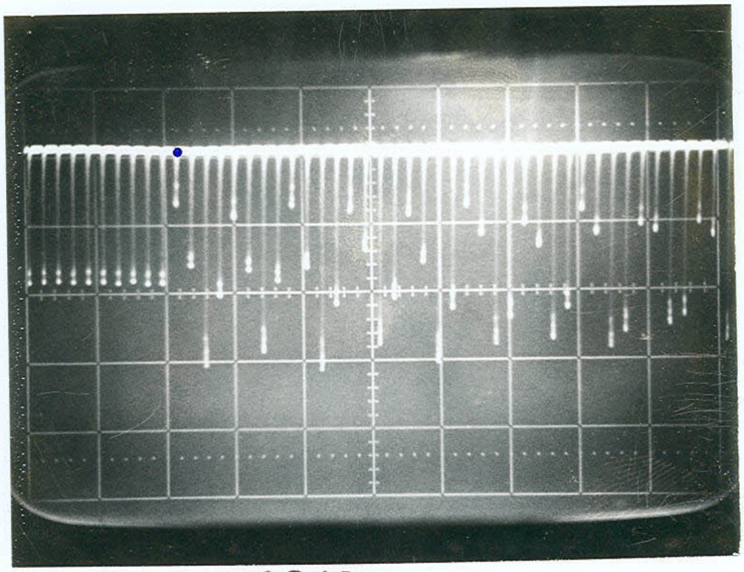
2. Description of the Experiment

By firing the air-core pulsed dipole (pinger) at station F38, a radial betatron oscillation can be initiated at any point in the main-ring cycle. The behavior of radial and vertical betatron oscillations on subsequent turns may then be observed with the aid of the position electrodes and associated circuitry.

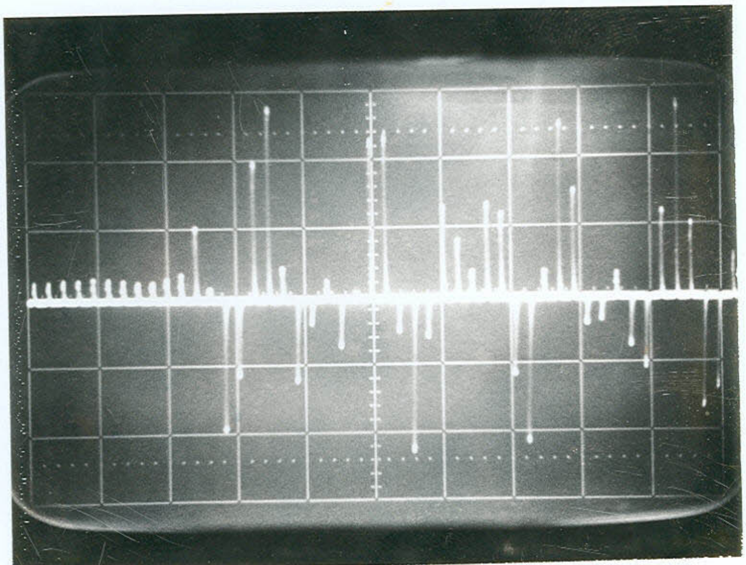
For example, consider the two oscilloscope traces reproduced on the following page. The upper picture is the radial position of consecutive turns at station F48; the lower picture is the vertical position at F49. The energy is 169 GeV. For the first ten turns on each picture, the beam is unperturbed. The negative signal at F48 indicates that the beam is inside the center line; the small positive signal on the vertical electrode says that the beam at F49 is a little

100 μsec/cm

0.1 v/cm



RF48



PF49

above the center of the detector. From the conversion factors

Radial: 2.3 inch/volt = 5.8 cm/volt

Vertical: 0.9 inch/volt = 2.3 cm/volt

one concludes that the equilibrium orbit is 1.1 cm inside at F48 and something less than a millimeter high at F49.

Then the pinger is fired, causing an inward deflection of the beam the next time it passes F38. The picture shows that by the time the beam passes F48 on the same turn, it is displaced outward by 6 mm. The displacements exhibited by successive turns indicate that the beam is undergoing a radial betatron oscillation with about quarter integral tune. In the vertical plane, no effect of the radial perturbation is noticeable on the first passage after the "ping," but by the time of the next passage a substantial vertical oscillation has already been established. In contrast to the radial case, the vertical displacements on successive turns do not show a simple tune pattern; this is not surprising but is what one would expect for coupled motion. In fact, if the modulation of the radial amplitude due to coupling were substantial, the radial displacement pattern would also appear irregular.

The amplitude of the betatron oscillations at each passage cannot be obtained from measurement at a single detector in each plane; rather one must measure the displacement at several neighboring detectors covering at least one half wavelength of the oscillation to determine the amplitude on a given turn.

The experiment was carried out in three stages. First, observations were made as described above to study the amplitude growth of the vertical motion. Figure 2 gives the vertical amplitude at the end of F sector versus the number of passages after the firing of the pinger, and Figure 3 the corresponding information for the radial direction.

According to Figure 2, the vertical amplitude goes through a complete cycle in ten turns--consistent with our typical tune split of 0.1. The vertical amplitude grows to two-thirds of the maximum radial amplitude; by conservation of energy, one would expect a 25% modulation of the radial amplitude. Since there is considerable noise in the

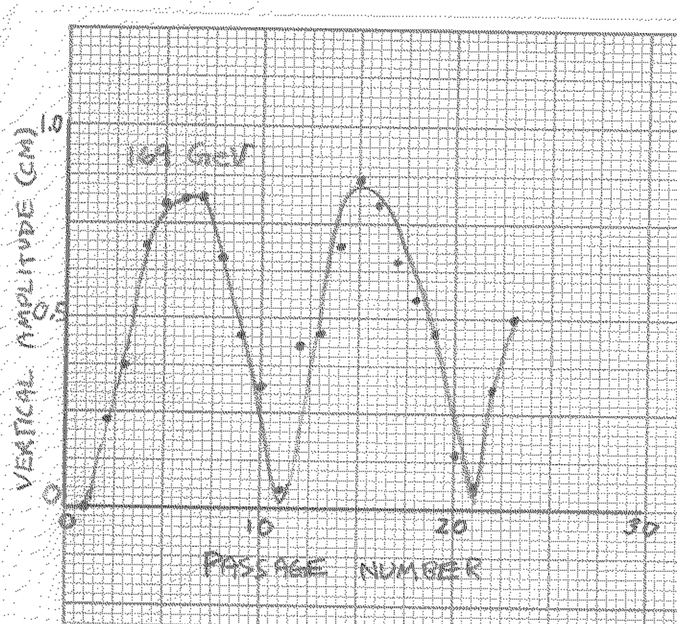


FIGURE 2

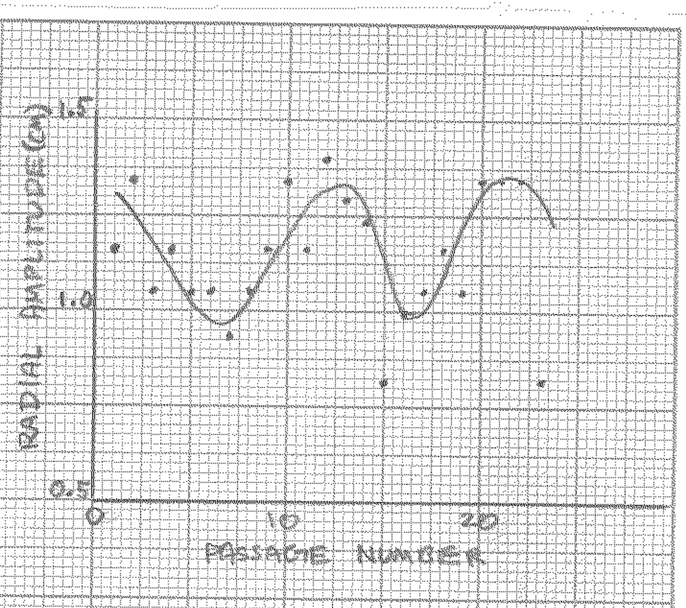


FIGURE 3

radial amplitude data, one can only say that the modulation in Figure 3 is about right.

Figure 4 shows the vertical amplitude at the end of each sector for four turns after excitation of the radial oscillation. One can see that the coupling does not arise from one or two places in the ring; rather, the sources are distributed.

FIGURE 4

In Figure 5, we plot the radial and vertical displacement versus station location at the end of F sector after one turn. The two waves differ in phase by about $\lambda/4$. The observation that the vertical wave is crossing the axis in the upward direction where the radial displacement is a maximum outward suggests the "handedness" of the coupling

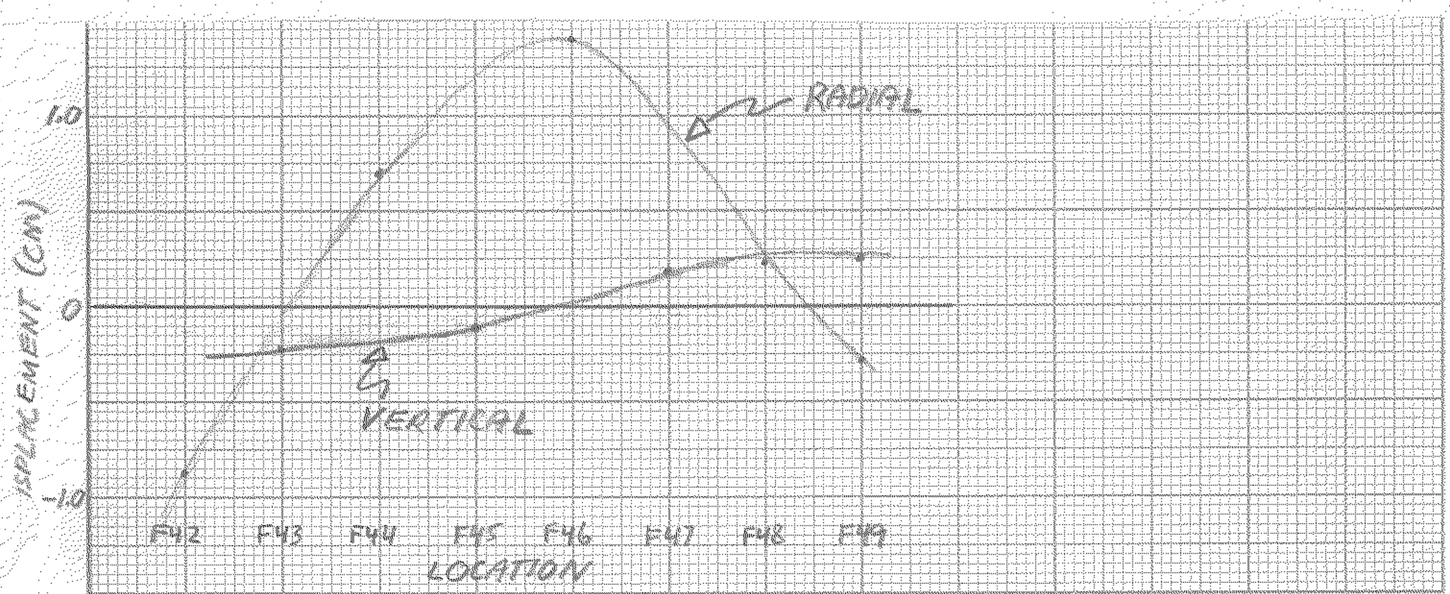


FIGURE 5

The first phase of the experiment concluded by verifying that the main features of the coupling, as shown in Figures 2, 3, and 5, were independent of radial position and pinger amplitude.

The second stage of the experiment consisted of rolling the six station 25 quadrupoles through the same angle, and remeasuring the coupling. The reasoning used to arrive at these quad moves was as follows.

Though in general the phase of the vertical motion with respect to the radial may take on any value for various distributions of skewing elements, a very simple distribution--namely, zeroth harmonic--will produce the observed $\lambda/4$ phase difference. Thus, a first attempt at corrective action suggests itself: roll a number, say six, of symmetrically placed quadrupoles of the same focusing character through the same angle. The sense of the angle is, of course, that which will produce a vertical motion of opposite sign to that which was observed;

i.e., the larger radius sides of vertically focusing quads should be moved downward by the roll, and the reverse for radially focusing quads. The fraction of the radial amplitude appearing in the vertical after one turn for this symmetric skewing is approximately $2\delta N$, where δ is the angle through which each of the N quads is rolled. The observed ratio is about 1/5; the desire to attempt a half correction initially lead to the selection of an 8 milliradian roll angle.

A remeasurement of the vertical and radial amplitudes as a function of the number of turns following the ping produced the data plotted in Figure 6 and 7 below. Now the ratio of the maximum vertical amplitude

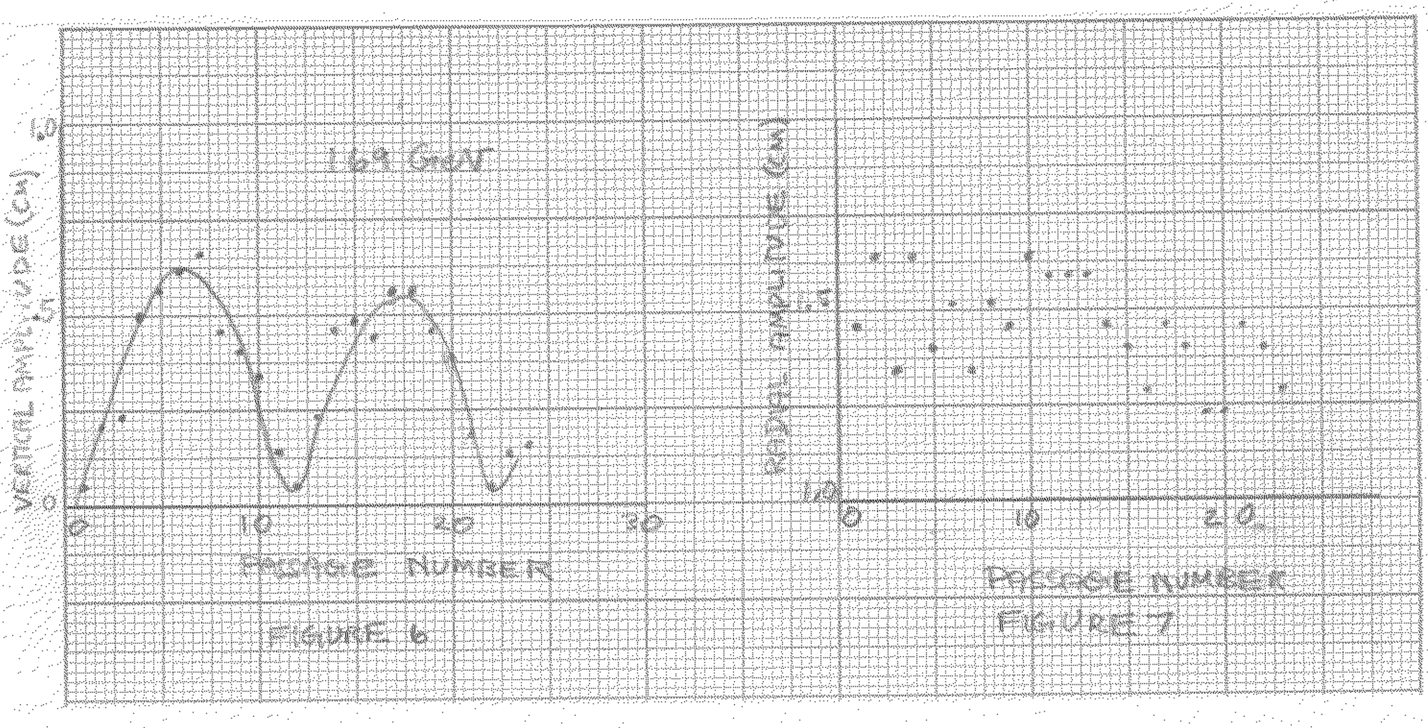


FIGURE 6 FIGURE 7

to the maximum radial amplitude is about four tenths. Since the coupling has been reduced, it takes a bit of imagination to extract the modulation in the radial plane from Figure 7.

In Figures 8 and 9, we plot results at 47 GeV; the resemblance with Figures 6 and 7 indicates that there is no strong energy dependence.

The third step in the experiment involved rolling six more quads--those at station 43--by 8 milliradian in the same sense as before. Figures 10 and 11 show the results of subsequent measurements at 169 GeV. The vertical amplitude is now a factor of ten less than the radial amplitude.

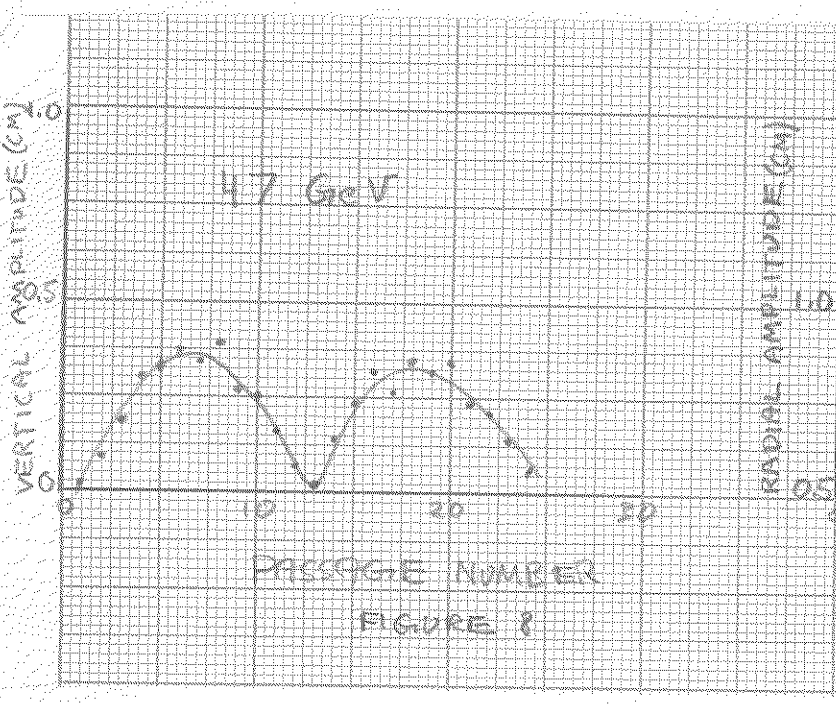


FIGURE 8

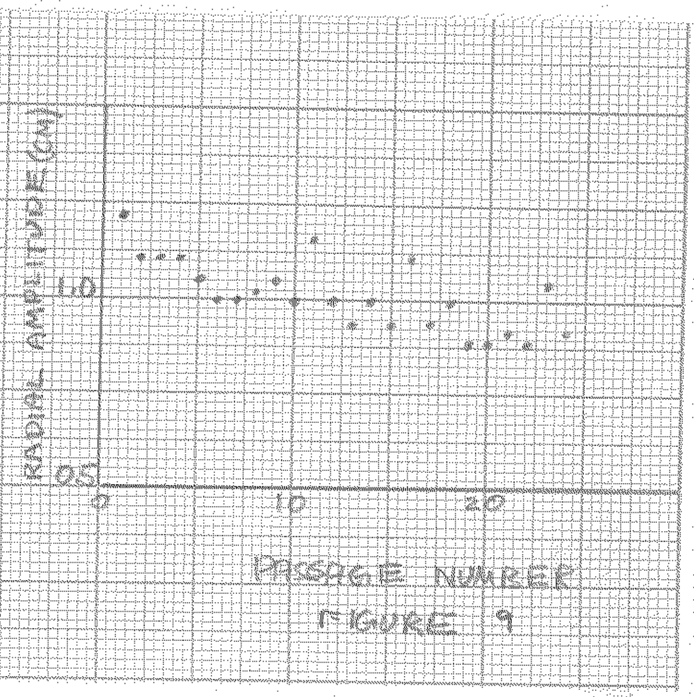


FIGURE 9

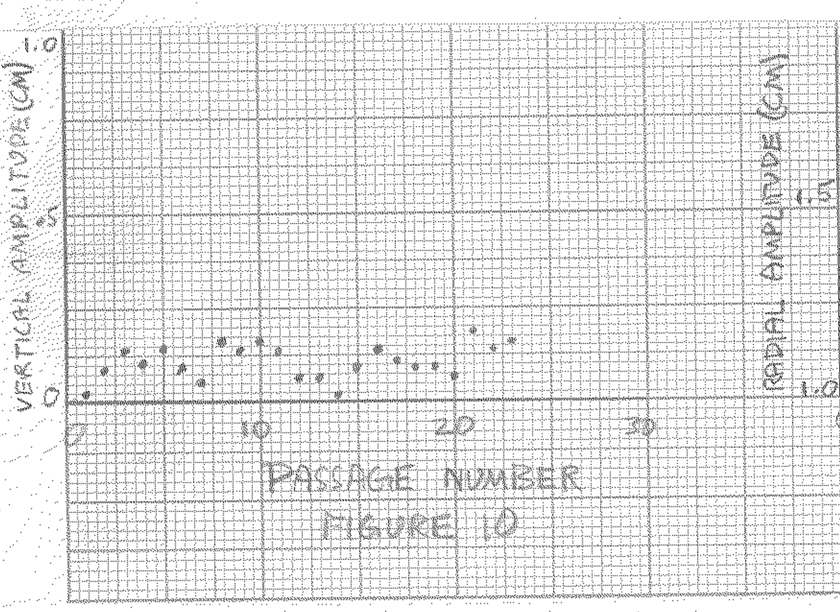


FIGURE 10

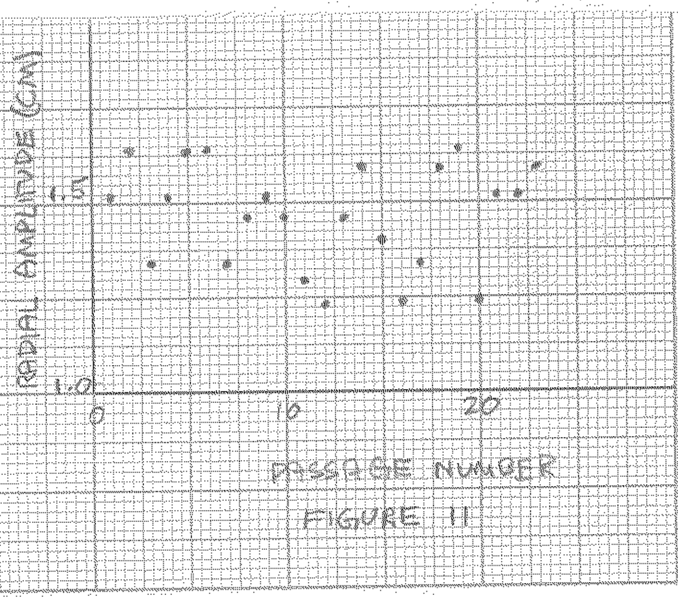


FIGURE 11

The above completed, at least for the time being, the high-energy phase of the coupling investigation. At this writing, study of the low-energy region is in progress, and we will defer further analysis of the present experiment so that we may combine the low and high-energy discussion in one report.

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